SZ effect or Not? - Detecting most galaxy clusters' main foreground effect

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ABSTRACT
Galaxy clusters are the most massive objects in the universe, and they comprise a high temperature intracluster medium of about 10^7K, believed to offer a main foreground effect for the CMB data with thermal Sunyaev-Zel'dovich (SZ) effect. This assumption has been confirmed with SZ signal detection in hundreds of clusters, but comparing with the huge numbers of clusters within optical selected samples from SDSS data, this only accounts for a few percent. Here we introduce a model-independent new method to confirm the assumption that galaxy clusters offer the thermal SZ signal as their main foreground effect. For the WMAP 7year data, we classified data pixels as "to be" or "not to be" affected by the sample clusters, with a parameter of its nearest neighbor cluster's angular distance. By comparing the statistical results of these two kinds of pixels, we can see how the sample clusters affect the CMB data directly. We find that Planck-ESZ sample and the Xray samples($\sim 10^2$ clusters) can lead to obvious temperature depression in WMAP 7year data, this confirms the SZ effect prediction. However, each optical selected sample ($> 10^4$ clusters), shows an opposite result: the mean temperature rises to about 10 uK. The unexpected qualitative scenario implies that the main foreground effect of most clusters is NOT always the expected SZ effect. This is maybe the reason why the SZ signal detection result is lower than what is expected by the model.

Key words: cosmic microwave background — galaxies: clusters: general — methods: statistical

1 INTRODUCTION

As the most massive self-gravitating systems in the cosmos, galaxy clusters can make significantly contribute to the mensuration of precision cosmology and during their formation and evolution various effects can be analyzed statistically. One major effect is the Sunyaev-Zel'dovich (SZ) effect (Sunyaev-Zel'dovich 1972) : the CMB photons can have inverse Compton scattering with high energy electrons in intracluster medium when passing through clusters. The thermal SZ effect is considered to be the most remarkable effect, as it can increase photons' energy statistically and noticeably distort the CMB spectrum. The thermal SZ effect decreases intensity in low frequencies(like Q, V, W band of WMAP) and increases intensity in high frequencies.

This predictable distortion of CMB data is expected as the marked signal of clusters. After the SZ signal of residential clusters was confirmed, the blind sky surveys using SZ effect have continued over the last decade, including SPT (Arthur et al. 2006), ACT (Carlstrom et al. 2011), PLANCK (Planck 2006) and so on. A number of high redshift clusters are expected to be found via the blind SZ sky surveys using features of SZ signal and its insensitive property on red shift (Carlstrom. et al. 2002). This provides a solid foundation for the mensuration of precision cosmology.

Here we notice a basic assumption is behind the expectations of these ongoing projects: the main foreground effect of most galaxy clusters to the CMB data, should be the expected thermal SZ effect. Though people have already detected and confirmed hundreds of clusters' SZ signal, we cannot assume that this is the case for all clusters. Comparing with the huge cluster numbers in optical selected samples from SDSS data, the basic assumption has only been validated in a few percent of clusters (and it is hard to provide their selection function (Planck Collaboration. 2011a)).

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Considering its unknowns can have unpredictable or unforeseen impacts on understanding or applying the results of SZ effect galaxy cluster survey, therefore we need a direct detection of most clusters to confirm this assumption.

At the same time, the cosmological analysis methods such as "cluster number count" et al.(Gilbert Holder et al. 2001; Manera & Mota 2006) expect a complete catalogue of setting conditions. It's important to make sure that the SZ effect signal blind survey of galaxy clusters will not miss cluster samples. However, some studies have already found the observed SZ effect signal to be (especially for optical selected clusters) not strong enough (Bielby et al. 2007; Lieu et al. 2006; Planck Collaboration. 2011a; Diego et al. 2003; Draper et al. 2012; Neelima Sehgal et al. 2012)(though still in debate (Planck Collaboration. 2011b; Afshordi, Niayesh et al. 2007; Melin 2011)),which implies the existence of other considerable foreground effects of clusters will contaminate the SZ effect signal. The existence and negligibility of SZ effect signals is becoming a noteworthy debate. We notice that some traditional analysis methods are model-dependent and the free parameters can lead to uncertainty in the debate. It is necessary to introduce a model-independent new method that will ensure more reliable conclusions can be drawn.

2 METHODS

For the main sample galaxy cluster we used typical size of five Mpc/h at $z \sim 0.5$ distance, its angular size (for ΛCDM model) is about six arcmin. This is round one pixel size of a Healpix data (N_{side}=512). So these objects appear as "points source" and will quickly "disappear" in the background noise when convolved with a beam as wide as WMAP's beams. It is hard to detect and confirm each single cluster's SZ signal. However, their statistical effect will not disappear. One can take help from the viewpoint of CMB data pixels, just take each pixel as a probe. To study the foreground effect of one galaxy cluster in an ideal isotropy CMB, a simple method is used to compare the probe data (temperature data of this pixel) of angular regions affected by the cluster or not. For real CMB data, the fluctuation temperature of each pixel can be taken as the detector's another Gauss distribution error. Considering the different properties of noise signals and the SZ signal, one can use statistical method to compare the mean probe data of angular regions of "to be" or "not to be" regions affected by the sample clusters. The noise signal will have similar effects on these two kinds of pixels but the thermal SZ signal will only depress the temperature of "to be" affected pixels.

The preconditions here are two points: First, we are able to assort these two angular regions; Second, each region includes enough data pixels to minimize the statistical error.

We find a continuous parameter d_1 is competent for such taxology. For each CMB data pixel, d_1 is defined as the angular distance of this pixel to its nearest neighbor galaxy cluster (of the cluster sample used). Comparing the traditional "stacking method" can help us understand the parameter d_1. The stacking method selects each cluster as the origin and bin pixels by circular rings around it (with different angular distances), and stacking annulus of all clus-
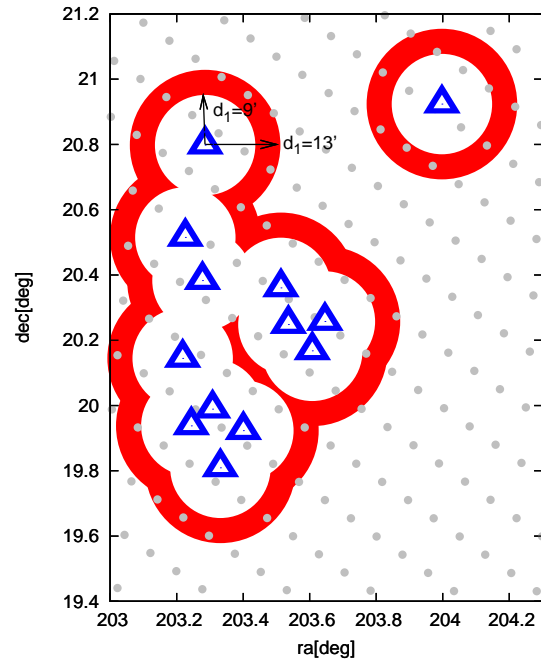

Figure 1. Pixel region round a group of cluster within a bin value of $9' < d_1 < 13'$. Each trigon correspond to the position of one cluster in GMBCG sample, and each gray disc means the central position of one pixel in WMAP data. For sparse cluster sample(the up-right one), we can see our method will simply retrogress to the stacking method.

ters to do analysis. Considering that galaxy clusters tend to swarm together, the temperature signal of pixels within annulus round one clusters can be seriously affected by its neighbor clusters. In Fig.1, we show the pixel region around a group of clusters within a bin value of d_1. Our method can be comprehended as changing the circle annulus around each cluster with curved loops around the collection of sample clusters, and redefining the angular parameter as d_1. This means the angular distance to the whole cluster sample is used rather than with each cluster.

As clusters mainly affect their local angular region, pixels with d_1 parameter large enough can properly represent the "not to be" affected angular regions unlike the stacking method. One other technical merit here is the impartial use of pixel data, as the stacking method applies pixels affected by neighbor clusters more times. When the cluster sample is sparse in the sky, our method simply reverts to the stacking method.

Here we illustrate the results with optical selected GMBCG (Jiangang Hao et al. 2010) galaxy cluster sample. In Fig.2, we show the distribution function of pixels' d_1 parameter. The figure shows the effective statistical region is within $0 < d_1 < 40'$. By comparing the possible angular size that one cluster might affect pixel data (mainly the beam size), one can see both the cluster affected region and unaffected region that contain enough pixels for effective statistical analysis. In contrast, due to the angular resolution of WMAP data, this is difficult to do with SDSS galaxy samples.

We can do analysis with the $< T >$–$< d_1 >$ curve (hereafter TD curve), by taking each pixel as a probe, comparing
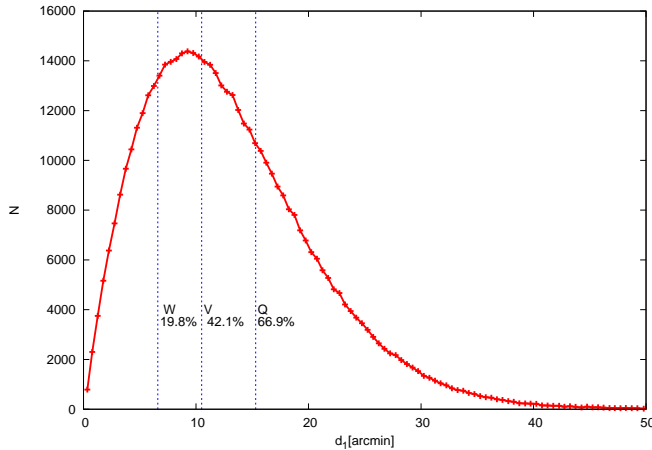
Figure 2. The distribution function of pixels' d_1 parameter. The pixels correspond to the CMB data within the main angular region of GMBCG sample. We select the 50580 clusters of the sample in the main survey area of SDSS DR-7 and take 503740 WMAP data pixels within the area as our statistical CMB angular region. In order to avoid some unwanted edge effect, we have already dropped pixels close to the edge within 70'. The blue lines show the beam size of WMAP data in Q, V, W band, respectively. And the percentages are the proportions of pixels whose d_1 value are within these half beam size.

Figure 3. Comparing the mean temperature of pixels with different d_1 parameter. The figure show typical TD curves of different CMB data - galaxy cluster samples. The temperature distribution function of pixels within each d_1 bin (3') can be well described with a Gauss function, and we calculate the error bar of $< T >$ with $\sigma = \sqrt{\frac{\sum (T_i - <T>)^2}{N(N-1)}}$ (N is the pixel number within the d_1 bin). The curves can be described with an empirical line function: $< T >= A* < d_1 > + T_1$ (fitting with weight $\sqrt{N}$). The traditional stack method is somehow our special case when the cluster sample is sparsity and the neighbor-cluster effect can be neglected, this is the case of Planck-189 sample. For the Planck-189 sample, we select WMAP data pixels round each cluster within 55' as our statistical region (bin-width is 5.5'). Since only the slope A is really interested , the WMAP(ilc)-Planck(189) cluster TD curve is translated as $< T > -13uK$ here, to show more clear contrast with same $< T >$ in unaffected region.

the mean temperature $< T >$ of pixels binned with different d_1 value. The merits of this method will be discussed in detail in another paper. Here we emphasize two points in physics:

First, the two sides of the TD curve represent different cases of pixels being affected or not (by the cluster sample used). The main foreground effects of galaxy clusters that we are interested in (such as SZ effect and radio emission) have the property of "angular localization", which means they only affect the angular region they appear in (within several arc-minutes for most clusters). Since the beam angle of WMAP data in Q,V,W band and ILC data ranges from 13' to about 30', it is safe to say pixels of $d_1 \rightarrow 40'$ represent angular regions "surely unaffected" and the $d_1 \sim 0'$ pixels represent "affected regions" by the cluster samples. By comparing the mean temperature of these two cases, we can see how galaxy clusters affect CMB data directly.

Second, some background or foreground unrelated objects outside the cluster sample might also affect the CMB data, but statistically they'll change the two side of the TD curve in the same way. This can be tested by simulation. So, if a reliable difference on the two side is confirmed, it should be the effect caused by the cluster sample itself.

Now we can see the qualitative scenario about how the cluster sample affect the TD curve: When thermal SZ effect being the main foreground effect, the mean temperature of WMAP data in Q, V, W bands should noticeably decline for cluster regions($d_1 \rightarrow 0'$), and the large d_1 side should remain unaffected. Then, the TD curve should rise from $d_1 = 0'$ to $d_1 = 40'$. In contrast, if radio emission was the main foreground effect, the low d_1 side would be driven up and the TD curve would be decline.
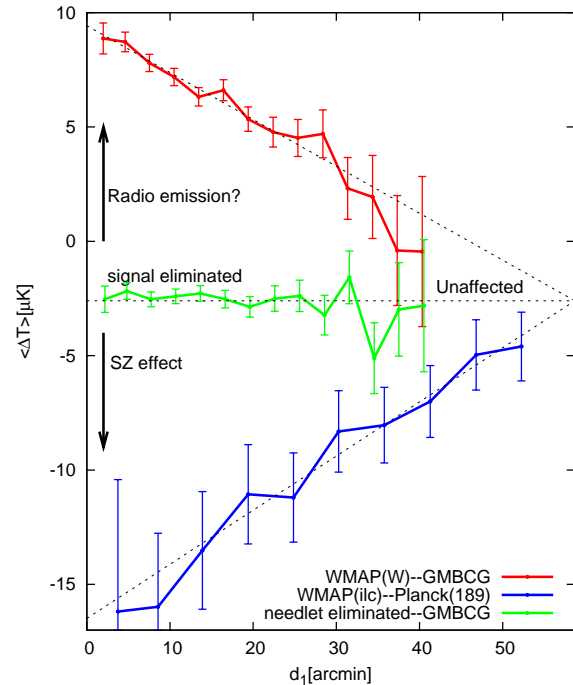
3 RESULTS

In Fig.3, we illustrate the TD curve of optical selected GMBCG sample (Jiangang Hao et al. 2010) and Planck SZ effect selected 189 clusters (Planck Collaboration. 2011a) (Planck-189). For Planck-189 sample, the TD curve line is obviously rising, which means $< T >$ is much lower when $d_1 \rightarrow 0'$ than that in large d_1 region, thus well confirming the SZ effect prediction. However, when the foreground is changed to the 50,580 clusters of GMBCG sample, we get an unexpected opposite result: the TD curve becomes a visible downward curve, which means the mean temperature behind clusters has got an increment up to about 10uK. This result is similar for WMAP data in Q,V,W bands and also the ilc data, with small error margins. (While, the TD curve becomes a nearly level line when we use the CMB data eliminated by another team (Delabrouille et al. 2009) using needlet method.)

As a post hoc examination, we also calculated the TD

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CMB–cluster	$N_{cluster}$	$\Delta T_A \equiv -A*40'$	$\Delta A/A$
WMAP(W)–GMBCG	50580	8.2 μK	6.9 %
WMAP(Q)–GMBCG	50580	7.3 μK	4.5 %
WMAP(V)–GMBCG	50580	6.5 μK	8.9 %
WMAP(ilc)–GMBCG	50580	6.9 μK	5.0 %
WMAP(W)–Wen	83279	6.3 μK	20.3 %
WMAP(W)–maxBCG	13823	5.3 μK	21.7 %
WMAP(W)–ACT	23	-19.4 μK	25.1 %
WMAP(ilc)–ACT	23	-11.5 μK	17.3 %
WMAP(W)–Planck(189)	189	-23.5 μK	25.0 %
WMAP(ilc)–Planck(189)	189	-9.5 μK	7.0 %
WMAP(W)–xcs3	503	-7.9 μK	32.2 %
WMAP(ilc)–xcs3	503	-6.8 μK	15.3 %
WMAP(W)–MCXC	1743	-7.7 μK	23.6 %

Table 1. Fitting results of different samples.

Figure 4. The TD curves of testing data of CMB and clusters. This figure includs: 1, randomized cluster sample (of GMBCG); 2, simulated CMB data in Q,V,W band; 3, reversal of CMB ilc data r180($ra \to ra+180°$), n2s($dec \to -dec$). For all the CMB data, we select the 503740 pixels within GMBCG's main region. (Since it's not using all-sky pixels, we are common to see their mean temperature is not zero.)

curves using the simulated CMB data of WMAP, and also the simulated random distributing cluster sample. For these, no causal relationship data were found, Fig.4 shows their TD curves are common level curves as expected.

Fig.3 also shows us that the TD curves of different samples are typically approximately straight lines, so we can describe them with an empirical line function:

$$< T >= A* < d_1 > +T_1$$

If we are not using one all-sky cluster sample, the parameter T_1 can be influenced by the cluster sample region and also the CMB large scale fluctuation. The valuable parameter is the A slope. For the samples we used, the value $\Delta T_A \equiv -A*40'$ can roughly show us the difference of $< T >$ between affected and unaffected regions, which underlies how these cluster samples affect the CMB data. $\Delta T_A < 0$ correspond the result of thermal SZ effect and $\Delta T_A > 0$ relate to opposite effect like radio emissions.

In table1 we show the value of ΔT_A when setting different cluster samples as foreground of WMAP 7-year data (Gilbert Holder et al. 2011) (W band and ilc data) . Here we can see the ΔT_A values fall explicitly in two situations: for the SZ effect selected and Xray selected cluster samples (ACT (Marriage, Tobias 2011), Planck-189 (Planck Collaboration. 2011a),xcs3 (Mehrtens, Nicola et al. 2011),mcxc (Piffaretti et al. 2011)) , ΔT_A is obviously negative, confirming the SZ effect image; yet for each optical selected cluster samples (GM-BCG (Jiangang Hao et al. 2010), Wen (Wen et al. 2012), maxBCG (Koester et al. 2007)), the ΔT_A value is significantly positive.

4 DISCUSSION AND CONCLUSIONS

Before quantitative study about ΔT_A value in more detail, we focus on the explicit $\Delta T_A > 0$ property of each optical selected cluster sample. Its value is about zero when we use a random distributed foreground sample in Fig.4. It is interesting to understand why ΔT_A changes in Fig.3. The $\Delta T_A < 0$ case of Planck-189 (Planck Collaboration. 2011a) corresponds to thermal SZ signals directly, then the unexpected $\Delta T_A > 0$ case of GMBCG sample with their main foreground effect on WMAP data is NOT the expected SZ effect.
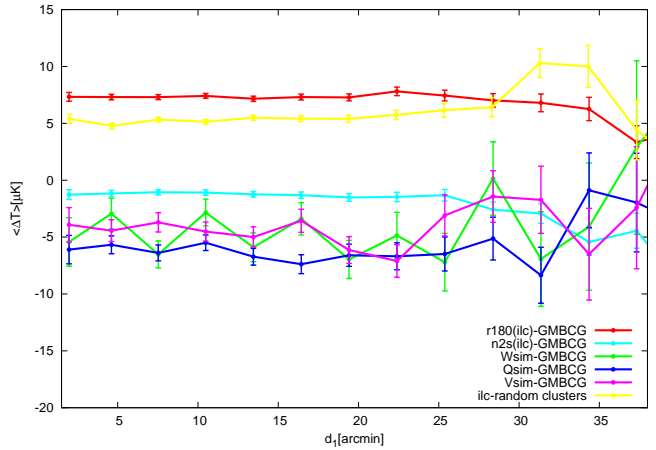
Such a result implies the existence of serious radio emission like effect in these optical select clusters, and this scenario clarifies why the SZ effect signal is apparently weaker than expected (Planck Collaboration. 2011a; Diego et al. 2003; Draper et al. 2012; Neelima Sehgal et al. 2012) :

• In angular regions of galaxy clusters, there exists an opposite contamination foreground effect something like radio emission that can affect the SZ effect signal detection. Such an opposite signal in most clusters is high enough that it can cover the SZ effect signal of the cluster, and being the main foreground effect. It should not be neglected when doing CMB signal analysis(soever they are surely clusters or not).

• In distance, this contamination should come from the cluster itself. Because if it affects on the line of sight before or after the clusters, such as the star burst galaxy at high redshift background, statistically there should also be the same effect at the non-cluster regions, and not result in a temperature change.

• In spectrum, such "emission components" show similar effects on Q,V,W band, a little higher at high frequency.

In conclusion, our model-independent method shows the main foreground effect of most galaxy clusters directly. The results of known SZ signal selected clusters and Xray observed clusters confirm the traditional thermal SZ result. Unexpectedly, however, most clusters in optical selected samples' thermal SZ signal are contaminated (even covered) by something like radio emission. This may be the reason why the SZ signal detection result is lower than model expectations. This may also help us understand the cooling flow problem of galaxy clusters: if the unknown effect is surely radio emission, then it can imply the mean radio intensity in a special way, for these clusters are able to offer radio emissions (on average) at least covering their thermal SZ signal.

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